

①

ARMY RESEARCH LABORATORY



AD-A285 410

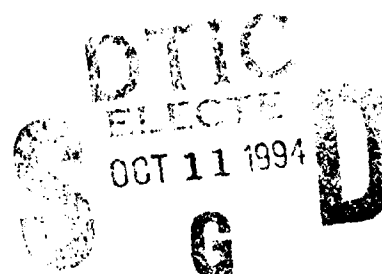


# Considerations in the Experimental Determination of Constitutive Parameters for Finite Strain Plasticity

Norris J. Huffington, Jr.

ARL-TR-576

September 1994



DTIC QUALITY INSPECTED 5

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

2318 94-31947



## **NOTICES**

**Destroy this report when it is no longer needed. DO NOT return it to the originator.**

**Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.**

**The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.**

**The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.**

**REPORT DOCUMENTATION PAGE**Form Approved  
OMB No 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

<b>1. AGENCY USE ONLY (Leave blank)</b>		<b>2. REPORT DATE</b> September 1994	<b>3. REPORT TYPE AND DATES COVERED</b> Final	
<b>4. TITLE AND SUBTITLE</b> Considerations in the Experimental Determination of Constitutive Parameters for Finite Strain Plasticity			<b>5. FUNDING NUMBERS</b>  PR: 1L162618AH80	
<b>6. AUTHOR(S)</b>  Norris J. Huffington, Jr.				
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  U.S. Army Research Laboratory ATTN: AMSRL-WT-TD Aberdeen Proving Ground, MD 21005-5066			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  U.S. Army Research Laboratory ATTN: AMSRL-OP-AP-L Aberdeen Proving Ground, MD 21005-5066			<b>10. SPONSORING / MONITORING AGENCY REPORT NUMBER</b>  ARL-TR-576	
<b>11. SUPPLEMENTARY NOTES</b>				
<b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b>  Approved for public release; distribution is unlimited.			<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT (Maximum 200 words)</b>  Various experimental procedures for measurement of quasi-static constitutive parameters for finite strain elastoplasticity are discussed in relation to counterpart finite element analyses of specimen deformation. It is concluded that the usefulness of such analyses is limited by the assumptions made in the formulations of current computer codes.				
<b>14. SUBJECT TERMS</b> stress-strain relations, finite element analysis, thin-walled tubes, elastoplasticity, ductile materials, torsion testing, hydrocodes, objective stress rates, finite strain, work hardening			<b>15. NUMBER OF PAGES</b> 19	
			<b>16. PRICE CODE</b>	
<b>17. SECURITY CLASSIFICATION OF REPORT</b> UNCLASSIFIED	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> UNCLASSIFIED	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> UNCLASSIFIED	<b>20. LIMITATION OF ABSTRACT</b> UL	

INTENTIONALLY LEFT BLANK.

## ACKNOWLEDGMENT

The author wishes to express his appreciation for many stimulating discussions with Dr. Joseph Santiago during the course of this investigation.

Accession For	
NTIS CRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification .....	
By .....	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

INTENTIONALLY LEFT BLANK.

## TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT .....	iii
LIST OF FIGURES .....	v
1. INTRODUCTION .....	1
2. HOLLOW CYLINDERS .....	2
3. WEDGE PROBLEMS .....	4
4. SOLID SPECIMENS .....	6
5. CONCLUDING REMARKS .....	8
6. REFERENCES .....	11
DISTRIBUTION LIST .....	13

INTENTIONALLY LEFT BLANK.

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	Geometry of the thin-walled torsion specimen . . . . .	2
2.	Ring-torsion problem gridding . . . . .	3
3.	Wedge of five radial elements . . . . .	4
4.	Stresses computed using the Jaumann stress rate . . . . .	5
5.	Stresses computed using the Green-Naghdi stress rate . . . . .	6
6.	Geometry for the solid wedge calculations . . . . .	7
7.	End views of wedge before and after shear banding . . . . .	7
8.	Suggested torsion test configuration . . . . .	9

INTENTIONALLY LEFT BLANK.

## 1. INTRODUCTION

There remain significant difficulties in the measurement of elastoplastic parameters for use in analysis of finite straining of relatively ductile materials. Ideally, one would prefer use of tests in which a single stress component (at a time) could be varied as a function of an associated strain component during which measurements of applied loads and corresponding deformations could be made on a test section of reasonable size in which a state of homogeneous stress exists. However, conventional uniaxial tests have shortcomings which limit their usefulness. Tension tests are limited to relatively modest strains by the inception of necking. Compression testing involves overcoming friction problems on end surfaces in order to obtain uniform axial stresses on these surfaces and avoid "barreling" (or interrupted testing of re-machined specimens). The torsion test is attractive in that shearing strains of 600% and greater have been reported for thin-walled tube specimens but also presents experimental and interpretational problems which will be discussed.

It may be recalled that Poynting (1909) studied finite torsion of wires while Swift (1947) performed tests on solid and hollow rods. Both reported an elongation of their specimens under finite twisting. Subsequently, Lindholm et al. (1980) (Johnson et al. 1983) employed a torsion specimen of the form shown in Figure 1, in particular for determination of material parameters for use with the Johnson-Cook (1983) constitutive model. White (1992) recently published a report in which the limitations on use of elementary analysis for interpretation of torsion test results were assessed by comparison with finite element calculations. It was found necessary to apply a correction factor to the rotation of the grips to allow for the deformation which occurs in the shoulder section of the Lindholm-type specimen. Unfortunately, this factor is a function of the specimen geometry and the flow stress function. Also, finite element calculations have revealed a tendency for tubes to decrease in diameter as the twist increases. When this is inhibited by the massive shoulder regions of the Lindholm specimen, longitudinal bending develops. Another concern with torsion testing of thin-walled tubes is the possibility of torsional buckling. To mitigate these problems, the gauge length of the Lindholm specimen is made quite short, making accurate optical measurements of strains almost impossible. Perhaps a more serious drawback is that there is essentially no portion of the gauge section which is in a homogeneous stress state.

In an effort to circumvent at least some of the problems cited previously, the author has studied designs of torsion specimens in which a longer gauge section can be employed but which would have to

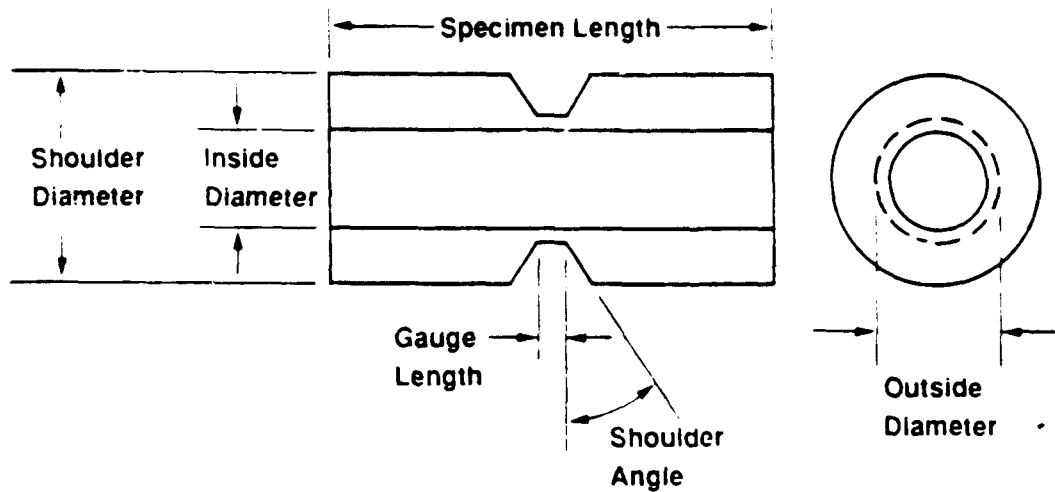


Figure 1. Geometry of the thin-walled torsion specimen.

be thick-walled or even solid to avoid buckling. There is a severe penalty associated with this approach. Whereas for the thin-walled tube, a mean shearing stress can be related to the applied torque by equilibrium considerations, it now becomes necessary to calculate the elastoplastic variation of stresses with the radius and this requires selection of a specific plasticity model. It was decided to perform the necessary calculations using rate-independent isothermal elastoplasticity, the von Mises yield function, and the associated flow rule.

The widely employed Lagrangian hydrocode DYNA3D (Hallquist 1983) provides these features in several of its material models. In particular, Model 10 accepts input of discrete data pairs representing points on an effective stress vs. effective plastic strain curve and interpolates for intermediate values as needed. This model originally only provided for isotropic work hardening, but the author has modified it to feature mixed isotropic/kinematic hardening as suggested by Hodge (1957). Also, the DYNA3D code has been altered to offer a choice between use of the Jaumann (1905) stress rate or the Green-Naghdi (1965) (Green and McInnis 1967) rate (polar decomposition of the deformation gradient). In the following, this code is employed to treat several boundary value problems pertaining to the torsion of hollow tubes and solid rods.

## 2. HOLLOW CYLINDERS

Consider the problem of a moderately thick ring composed of "brick" elements: 5 elements in the radial direction, 72 in the circumferential direction, and 1 in the axial direction (see Figure 2). The

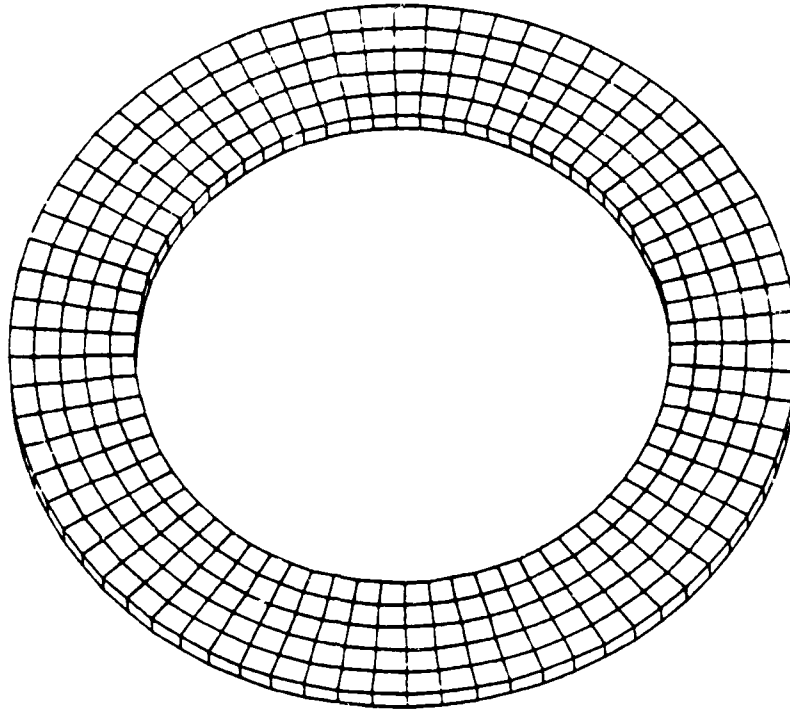


Figure 2. Ring-torsion problem gridding.

undeformed inner and outer radii of the ring are 0.315 in and 0.465 in, respectively, and the axial dimension is 0.030 in. The radial dimensions of each element are initially equal. The material data to be employed in Model 10 were derived from the quasi-static tests on annealed OFHC copper reported by Weerasooriya and Swanson (1991), 16 points on the effective stress vs. effective plastic strain curve being used as input. The density was taken to be  $0.000837 \text{ lb s/in}^4$ . The nodes are constrained to not move in the axial direction but are free to move radially. The two  $z = \text{constant}$  faces rotate in contrary directions at 1 rad/s and are given appropriate initial velocities to avoid a starting transient. Clearly, the solution of this idealized problem also applies to an infinitely long cylinder made of many such rings all subjected to the same loading. It also applies to the central portion of a finite fixed-ended cylinder sufficiently removed from the ends where torques are applied that a homogeneous state of stress exists. Except when it is desired to analyze the possibility of torsional buckling of the cylinder, it is possible to focus on the stresses and deformation of a single "wedge" of five radial elements, since all such wedges have the same deformation history (see Figure 3). Since the DYNA3D code does not have input options suitable for modeling the wedge problem, a special subroutine, T5RFIX, was introduced to apply the appropriate nodal constraints to duplicate the results of the ring calculations. Consequently, the rather voluminous results for the ring problem will not be shown but were used to check the validity of the wedge constraints.

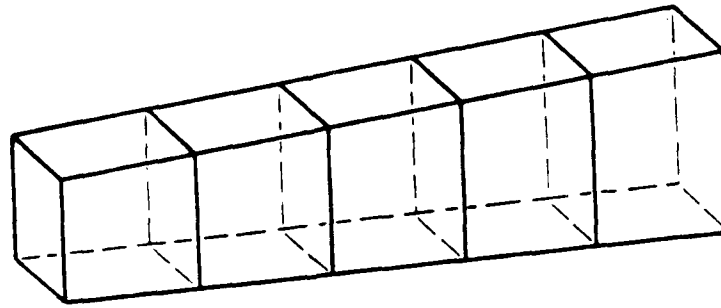


Figure 3. Wedge of five radial elements.

### 3. WEDGE PROBLEMS

A matrix of fixed-ended wedge problems was then studied for the possible combinations of isotropic and kinematic hardening and the Jaumann and Green-Naghdi stress rates, all run to a final torsional shear strain of  $\epsilon_{z\theta} \approx 2.0$  (tensor component). In the course of a convergence study, it was found that the major stress  $\sigma_{z\theta}$  is insensitive to the size of the wedge angle, but that computed values of the circumferential stresses  $\sigma_{\theta\theta}$  in the five elements were inconsistent with the requirement that the hoop force on any radial section should be zero in a statics problem. This cast doubt on the validity of all predicted normal stresses induced by the torsional loading. The difficulty appears to be associated with the brick element employed by DYNA3D. This element uses a single integration point located at its center; when the element experiences large shearing and warping, the stresses computed at the integration point are inappropriate for evaluating nodal forces since the actual stresses in the neighborhood of the nodes would vary significantly from those at the center of the element. This difficulty can be somewhat alleviated by reducing the thickness of the elements in the z-direction (which reduces the amount of circumferential stretch required to reach the desired shearing strain). Some effort was made to optimize the element thickness to minimize the hoop force and the results which follow are based on this concept.

Results from DYNA3D calculations for the fixed-ended wedge using the Jaumann stress rate for both isotropic and kinematic hardening are shown in Figure 4 for the middle element of the wedge. The isotropic hardening curve for the shearing stress is in good agreement with experimental data (Weerasooriya and Swanson 1991) and the induced normal stresses, while not zero, are too small to be visible with the scale employed. For the pure kinematic hardening case, the shear stress exhibits the widely noted sinusoidal behavior associated with the Jaumann rate, as do the induced normal stresses.

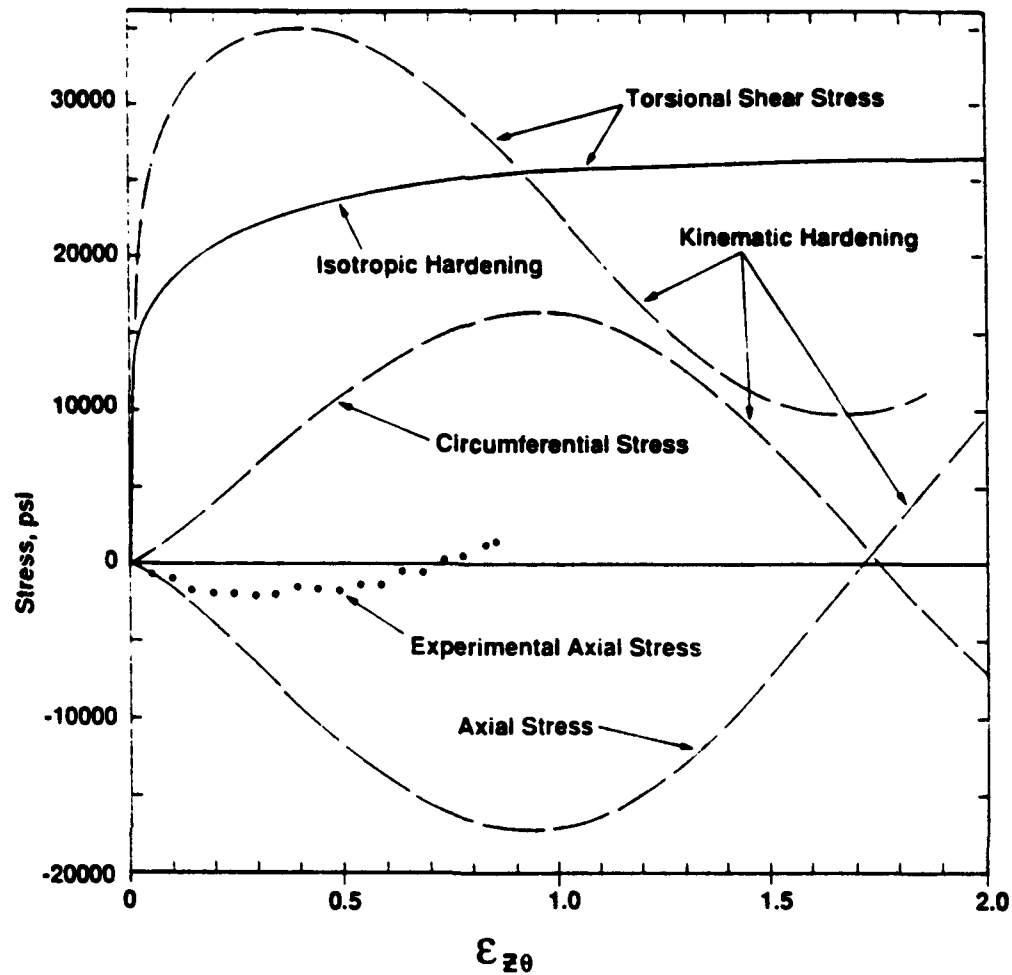


Figure 4. Stresses computed using the Jaumann stress rate.

The magnitudes of the latter stresses are unrealistically large and these stresses would significantly affect the effective stress function if actually present. The experimental curve for the induced axial stress is also shown in this figure. Calculations for a free-ended wedge were also made using the Jaumann stress rate for the isotropic case; the results were indistinguishable from the isotropic curves shown in Figure 4. Of course, there was an axial extension of the wedge and the magnitudes of the axial stresses were further reduced.

Calculations similar to those described previously were also performed using the Green-Naghdi stress rate and the results for a fixed-ended wedge are shown in Figure 5. For the isotropic case, the curves shown in this figure are essentially the same as those obtained using the Jaumann rate. In the kinematic hardening case, the early oscillatory behavior was avoided but the magnitudes of the induced normal stresses are still large.

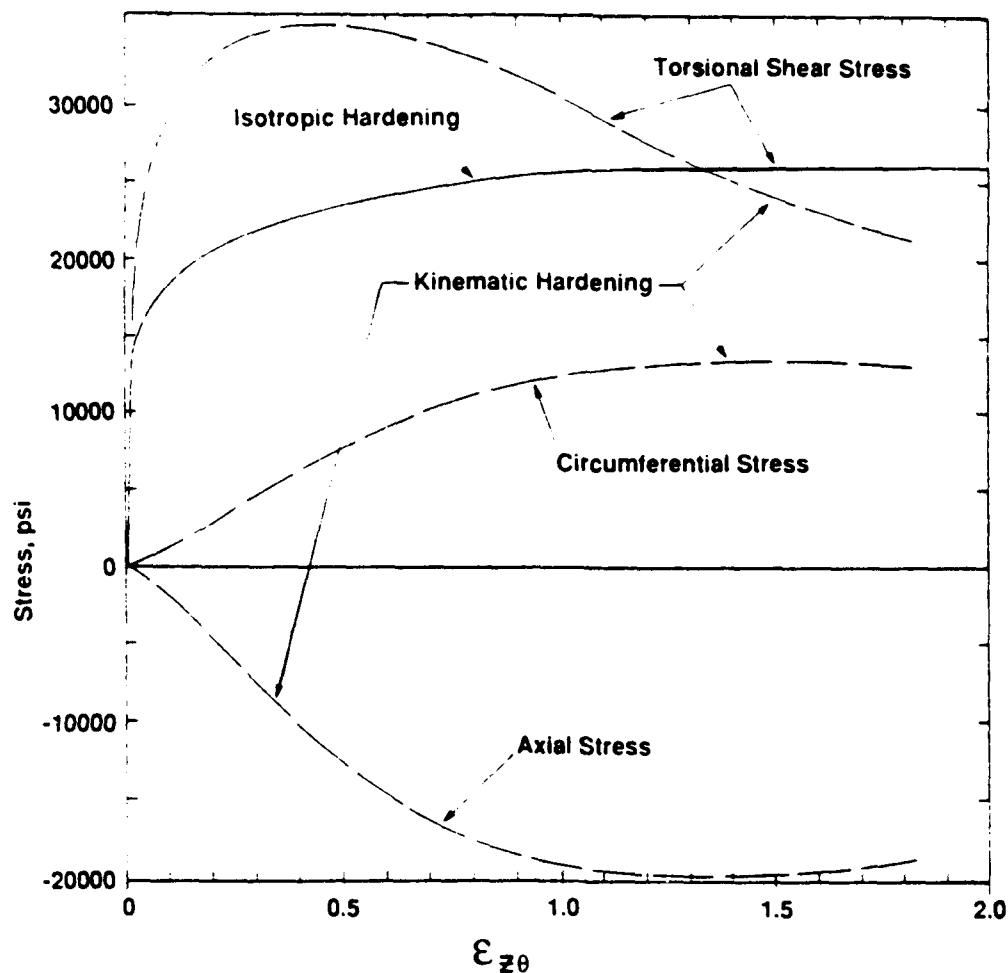


Figure 5. Stresses computed using the Green-Naghdi stress rate.

#### 4. SOLID SPECIMENS

In anticipation that torsional buckling of hollow, cylindrical specimens might preclude successful material characterization tests at large shear strains, a study of the feasibility of using DYNA3D calculations for test data interpretations (up to incipient buckling) was conducted. Again, it is not necessary to model the entire cross section, but only a "pie-shaped" wedge with appropriate constraints. To accomplish this, the DYNA3D code was modified to include subroutines TWED and TWED2, which apply to the geometry indicated in Figure 6.

A series of calculations were performed in which the nodes on the outer surface in the "grip" region were inhibited from moving in the axial direction and constrained to rotate about the Z-axis at specified angular velocities. The results of these calculations are too complex to cover in this report. However, it is worth noting certain new phenomena which arise in these calculations.

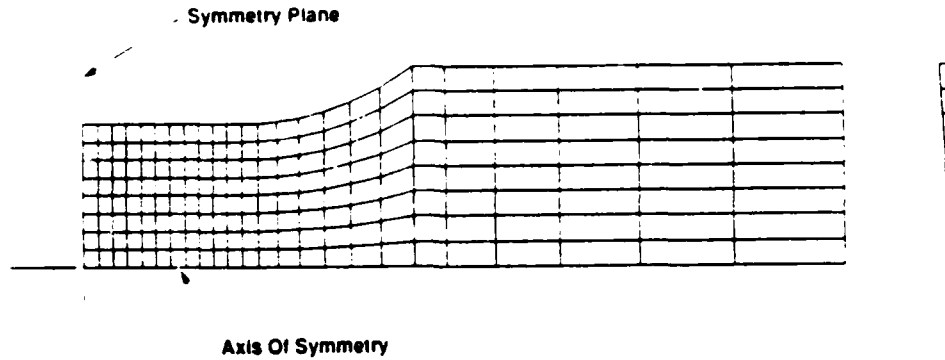


Figure 6. Geometry for the solid wedge calculations.

One of these is what may be termed "isothermal shear banding," which entails a spontaneous, rapid increase in plastic strain in an element or in all the elements at some axial location. This phenomenon is unrelated to thermal softening of materials since the mathematical model has no provision for thermal effects. Although this behavior is observed to a very limited extent during calculations using isotropic hardening, it is a serious destabilizing effect when kinematic hardening is employed. This banding is triggered in the most critically loaded element when the sinusoidally varying shear stress decreases from its first peak. Figure 7 shows end views of the twisting wedge before and after the appearance of the first band. Unlike adiabatic shear bands which progress to extreme localization, these isothermal bands tend to broaden as the banding spreads to adjacent elements.

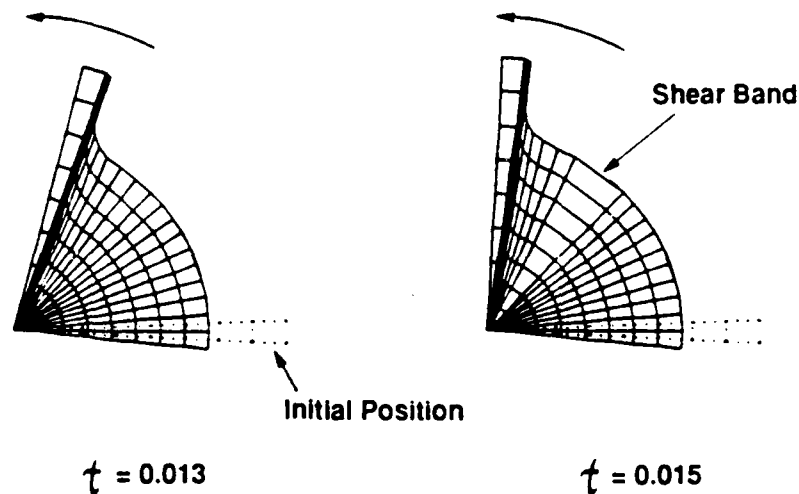


Figure 7. End views of wedge before and after shear banding.

Another phenomenon occurred during a mixed isotropic/kinematic calculation using the Green-Naghdi stress rate (made to assess the Bauschinger effect) in which the "grip" end was programmed to twist through  $280^\circ$  and then twist back to  $120^\circ$ . During the latter part of the reversed loading, the wedge was observed to buckle (computationally, but this may also occur in a physical experiment).

## 5. CONCLUDING REMARKS

It is the uncertainties regarding modeling plastic flow, work hardening, evolution of anisotropy, and objective stress rates which impede successful finite element modeling of experimental specimen configurations and motivate experimentalists to adopt simple shapes such as the thin-walled tube for which stress can be related to strain through equilibrium and geometric considerations.

The feasibility of modeling the torsion of hollow cylinder and solid rod specimens has been demonstrated in this report, but the results are conditioned by material modeling decisions. In view of this, the author does not feel that the tedious and expensive calculations required for a converged solution for the solid rod can be justified. Further study of modeling the hollow tube using various material representations and alternate finite elements may be worthwhile.

Where it is desired to use the thin-walled tube specimen, the configuration shown in Figure 8 may be considered. This configuration, which is very similar to that employed by Professor Swift (1947), consists of a straight, cylindrical tube with snugly fitted plugs of a high modulus material inserted in each end. The grips of a torsion tester would be applied in the region of the plugs. The gauge section of the tube must be relatively short to inhibit torsional buckling. Swift attempted to resist buckling by introducing a small clearance solid rod into the gauge section as part of one of the end plugs but had problems with binding between the rod and specimen. It would appear preferable to introduce a "free floating" solid rod and use today's super lubricants. Another method for delaying the onset of buckling would be to apply a uniform axial tension to the test specimen.

It should be remarked that elastoplastic parameters obtained by finite shearing or compression tests may no longer pertain to an isotropic material. It would be extremely valuable to be able to map the current yield surface to assess induced anisotropy, preferably in the same experimental apparatus.

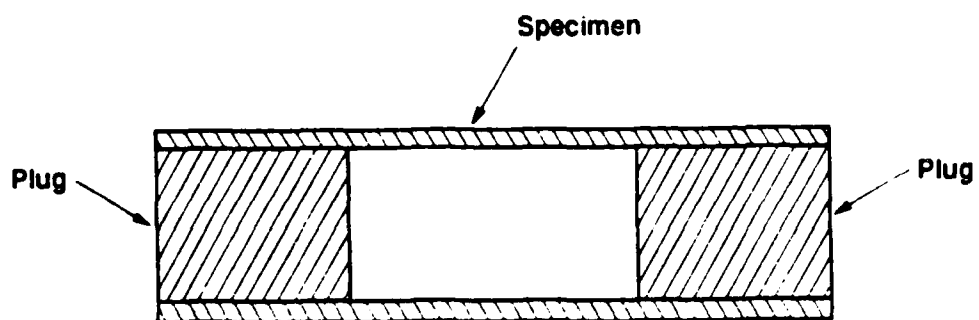


Figure 8. Suggested torsion test configuration.

INTENTIONALLY LEFT BLANK.

## 6. REFERENCES

- Green, A. E., and P. M. Naghdi. "A General Theory of an Elastic-Plastic Continuum." Arch. Rat. Mech. Anal., vol. 18, pp. 251-281, 1965.
- Green, A. E., and B. C. McInnis. "Generalized Hypo-Elasticity." Proceedings of the Royal Society of Edinburgh, A57, p. 220, 1967.
- Hallquist, J. O. "Theoretical Manual for DYNA3D." UCID-19401, University of California, Lawrence Livermore National Laboratory, 1983.
- Hodge, Jr., P. G. "Discussion of Prager (1956)." Journal of Applied Mechanics, vol. 24, no. 3, pp. 482-483, 1957.
- Jaumann, G. Grundlagen der Bewegungslehre. Leipzig, 1905.
- Johnson, G. R., and W. H. Cook. "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures." Seventh International Symposium on Ballistics, The Hague, April 1983.
- Johnson, G. R., J. M. Hoegfeldt, U. S. Lindholm, and A. Nagy. "Response of Various Metals to Large Torsional Strains Over a Large Range of Strain Rates - Part 1: Ductile Metals." ASME Journal of Engineering Materials and Technology, pp. 42-53, 1983.
- Lindholm, U. S., A. Nagy, G. R. Johnson, and J. M. Hoegfeldt. "Large Strain, High Strain Rate Testing of Copper." ASME Journal of Engineering Materials and Technology, pp. 376-381, 1980.
- Poynting, J. H. "On Pressure Perpendicular to the Shear Planes in Finite Pure Shears, and on the Lengthening of Loaded Wires when Twisted." Proceedings of the Royal Society of London, vol. A82, pp. 546-559, 1909.
- Swift, H. W. "Length Changes in Materials under Torsional Overstrain." Engineering, vol. 163, pp. 253-257, 1947.
- Weerasooriya, T., and R. A. Swanson. "Experimental Evaluation of the Taylor-Type Polycrystal Model for the Finite Deformation of an FCC Metal (OFHC Copper)." TR 91-20, U.S. Army Materials Technology Laboratory, Watertown, MA, 1991.
- White, C. S. "Use of the Thin-Walled Torsion Specimen." TR 92-49, U.S. Army Materials Technology Laboratory, Watertown, MA, 1992.

INTENTIONALLY LEFT BLANK.

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145	1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Materiel Command ATTN: AMCAM 5001 Eisenhower Ave. Alexandria, VA 22333-0001	1	Commander U.S. Army Tank-Automotive Command ATTN: AMSTA-JSK (Armor Eng. Br.) Warren, MI 48397-5000
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-SD-TA, Records Management 2800 Powder Mill Rd. Adelphi, MD 20783-1145	1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
3	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-SD-TL, Technical Library 2800 Powder Mill Rd. Adelphi, MD 20783-1145	1	Commandant U.S. Army Infantry School ATTN: ATSH-WCB-O Fort Benning, GA 31905-5000
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-SD-TP, Technical Publishing Branch 2800 Powder Mill Rd. Adelphi, MD 20783-1145		<u>Aberdeen Proving Ground</u>
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000	2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050	1	Cdr, USATECOM ATTN: AMSTE-TC
1	Director U.S. Army Advanced Systems Research and Analysis Office (ATCOM) ATTN: AMSAT-R-NR, M/S 219-1 Ames Research Center Moffett Field, CA 94035-1000	1	Dir, USAERDEC ATTN: SCBRD-RT
		1	Cdr, USACBDCOM ATTN: AMSCB-CII
		1	Dir, USARL ATTN: AMSRL-SL-I
		5	Dir, USARL ATTN: AMSRL-OP-AP-L

<u>No. of Copies</u>	<u>Organization</u>
1	HQDA (SARD-TT/Dr. F. Milton) WASH DC 20310-0103
1	HQDA (SARD-TT/Dr. J. Appel) WASH DC 20310-0103
2	Director U.S. Army Research Laboratory ATTN: AMSRL-VS, W. Elber AMSRL-VS-S, F. Bartlett Langley Research Center (Mail Stop 266) Hampton, VA 23681-0001
1	Director DARPA ATTN: J. Richardson 3701 North Fairfax Dr. Arlington, VA 22203-1714
1	Commander Defense Nuclear Agency 6801 Telegraph Rd. Alexandria, VA 22192
6	Director U.S. Army Research Office ATTN: I. Ahmad K. Iyer J. Wu G. Anderson J. Chandra Technical Library P.O. Box 12211 4300 Miami Blvd. Research Triangle Park, NC 27709
4	Commander U.S. Army Missile Command ATTN: W. McCorkle M. Cole Donald Lovelace Michael Schexnayder Redstone Arsenal, AL 35898-5250
1	Commander U.S. Army Belvoir RD&E Center ATTN: S. G. Bishop Fort Belvoir, VA 22060-5166

<u>No. of Copies</u>	<u>Organization</u>
5	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: T. Davidson V. Lindner J. Pearson E. Baker Technical Library Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: C. W. Kitchens Watervliet, NY 12189
1	Commander ASARDA ATTN: C. Kominos The Pentagon Washington, DC 20301
2	Commander U.S. Army Tank-Automotive Command ATTN: J. Thompson K. Bishnoi Warren, MI 48397-5000
7	Director U.S. Army Research Laboratory ATTN: L. Johnson A. Rajendran S. C. Chou J. McLaughlin T. Weerasooriya D. Dandekar Technical Library Watertown, MA 02172-0001
3	Commander Naval Weapons Center ATTN: Don Thompson, Code 3268 T. J. Gill Technical Library China Lake, CA 93555

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
2	Commander Naval Surface Warfare Center ATTN: William Mock Technical Library Dahlgren, VA 22448-5000
5	Commander Naval Surface Warfare Center ATTN: H. Mair R. Garrett P. Walter F. J. Zerilli Technical Library 10901 New Hampshire Ave. Silver Spring, MD 20903-5000
2	Director Sandia National Laboratories ATTN: D. Bammann L. Lipkin Livermore, CA 94550
1	Director Air Force Wright Laboratories Materials Laboratory ATTN: Dr. T. Nicholas Wright-Patterson AFB, OH 45433
4	Director Wright Laboratory ATTN: MNSH, W. Cook MNMW, J. Foster J. Collins Technical Library Eglin AFB, FL 32542
1	Commander U.S. Army Ballistic Missile Defense Systems Command ATTN: R. Becker P.O. Box 1500 Huntsville, AL 35807-3801

<u>No. of</u> <u>Copies</u>	<u>Organization</u>
8	Director Sandia National Laboratories ATTN: J. M. McGlaun P. Yarrington E. Hertel M. Forrestal D. Grady M. Kipp S. Silling Technical Library P.O. Box 5800 Albuquerque, NM 87185
16	Director Los Alamos National Laboratory ATTN: G. E. Cort T. F. Adams D. Mandell R. Karpp J. Dienes A. Zurek F. Addessio P. Follansbee J. N. Johnson W. Kawahara M. W. Lewis D. Rabern J. Repa L. Schwalbe S. Schiferl Technical Library P.O. Box 1663 Los Alamos, NM 87545
9	Director Lawrence Livermore National Laboratory ATTN: R. Tipton R. Whirley R. Christensen D. Baum R. Couch D. Lassila M. Murphy D. Steinberg Technical Library P.O. Box 808 Livermore, CA 94550

<u>No. of Copies</u>	<u>Organization</u>
1	Aerojet Precision Weapons Dept. 5131/T-W ATTN: J. Carleone 1100 Hollyvale Azusa, CA 91702
1	Battelle ATTN: B. D. Trout 505 King Ave. Columbus, OH 43201
3	Dyna East Corporation ATTN: P. C. Chou R. Ciccarelli W. Flis 3201 Arch St. Philadelphia, PA 19104
3	Southwest Research Institute ATTN: C. Anderson A. Wenzel U. Lindholm P.O. Drawer 28255 San Antonio, TX 78228-0255
1	Alliant Techsystems, Inc. ATTN: G. R. Johnson MN 48-2700 7225 Northland Dr. Brooklyn Park, MN 55428
1	S-Cubed ATTN: R. Sedgwick P.O. Box 1620 La Jolla, CA 92038-1620
2	Orlando Technology, Inc. ATTN: D. Matoska J. Osborn P.O. Box 855 Shalimar, FL 32579
1	Livermore Software Technology Corp. ATTN: John O. Hallquist 2876 Waverly Way Livermore, CA 94550
1	Rensselaer Polytechnic Institute ATTN: Prof. E. Krempl Troy, NY 12181

<u>No. of Copies</u>	<u>Organization</u>
2	Brown University Division of Engineering ATTN: R. Clifton B. Freund Providence, RI 02912
1	Carnegie-Mellon University Department of Mathematics ATTN: Dr. M. E. Gurtin Pittsburgh, PA 15213
5	The Johns Hopkins University ATTN: Prof. W. Sharpe Prof. J. F. Bell Prof. K. T. Ramesh Prof. A. Douglas Prof. R. E. Green 34th and Charles St. Baltimore, MD 21218
2	University of California at San Diego Department of Mechanical and Aerospace Engineering ATTN: Prof. S. Nemat-Nasser Prof. M. Meyers La Jolla, CA 92093
1	University of Delaware Department of Mechanical and Aerospace Engineering ATTN: Prof. J. Vinson Newark, DE 19711
2	University of Florida Department of Engineering Science and Mechanics ATTN: Prof. L. Malvern Prof. D. Drucker Gainesville, FL 32601
1	Virginia Polytechnic Institute and State University Department of Engineering Science and Mechanics ATTN: Prof. C. W. Smith, Jr. Blacksburg, VA 24061

<u>No. of Copies</u>	<u>Organization</u>
1	University of Maryland Department of Mechanical Engineering ATTN: R. Armstrong College Park, MD 20742
1	University of Missouri - Rolla Department of ME, AE, and EM ATTN: R. Batra Rolla, MD 65401-0249
1	Northwestern University Department of Civil Engineering ATTN: T. Belytschko Evanston, IL 60208
1	University of Virginia Department of Applied Mathematics ATTN: C. O. Horgan Charlottesville, VA 22903
1	Georgia Institute of Technology School of Mechanical Engineering ATTN: D. L. McDowell Atlanta, GA 30332

<u>No. of Copies</u>	<u>Organization</u>
	<u>Aberdeen Proving Ground</u>
27	Dir, USARL ATTN: AMSRL-WT-T, T. W. Wright AMSRL-WT-TA, G. E. Hauver AMSRL-WT-TB, N. M. Gniazdowski F. H. Gregory AMSRL-WT-TC, R. S. Coates W. S. de Rosset F. I. Grace K. D. Kimsey M. L. Lampson L. S. Magness W. P. Walters AMSRL-WT-TD, W. D. Allison A. M. Dietrich K. Frank A. D. Gupta J. T. Harrison N. J. Huffington J. H. Kineke M. N. Raftenberg G. Randers-Pehrson J. M. Santiago S. B. Segletes P. B. Simmers AMSRL-WT-PD, K. A. Bannister B. P. Burns W. H. Drysdale S. A. Wilkerson

INTENTIONALLY LEFT BLANK.

## USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number ARL-TR-576 Date of Report September 1994

2. Date Report Received \_\_\_\_\_

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

**CURRENT  
ADDRESS**

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

**OLD  
ADDRESS**

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)  
(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS



NO POSTAGE  
NECESSARY  
IF MAILED  
IN THE  
UNITED STATES

**BUSINESS REPLY MAIL**  
FIRST CLASS PERMIT NO 0001, APG, MD

Postage will be paid by addressee

**Director**  
**U.S. Army Research Laboratory**  
**ATTN: AMSRL-OP-AP-L**  
**Aberdeen Proving Ground, MD 21005-5066**

